

Experimental realization of large-alphabet quantum key distribution protocol using orbital angular momentum entanglement

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We experimentally demonstrate a quantum key distribution (QKD) protocol using photon pairs entangled in orbit angular momentum (OAM). In our protocol, Alice and Bob modulate their OAM states on each entangled pair with spatial light modulators (SLMs), respectively. Alice uses a fixed phase hologram in her SLM, while Bob designs N different suitable phase holograms and uses them to represent his N -based information in his SLM. With coincidences, Alice can fully retrieve the key stream sent by Bob without information reconciliation or privacy amplification. We report the experiment results with $N = 3$ and the sector states with OAM eigenmodes $|\ell = 1\rangle$ and $|\ell = -1\rangle$. Our experiment shows that the coincidence rates are in relatively distinct value regions for the three different key elements. Alice could recover fully Bob's keys by the protocol. Finally, we discuss the security of the protocol both from the light way and against the general attacks.

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I. INTRODUCTION

Quantum key distribution (QKD) allows two parties (typically called Alice and Bob) to generate a secret key in the presence of an eavesdropper (Eve). It performs the detection of any eavesdropping, and the security is guaranteed by the fundamental laws of quantum mechanics, such as, noncloning theorem and Heisenberg uncertainty (see ref.[1] and refs. therein). QKD has attracted a great deal of research interest since BB84 QKD protocol was reported [2].

Up to now, there have already been several typical QKD protocols [1–8]. For example, BB84 [2], B92 [3] and SARG04 [4] protocols are nonorthogonal single-photon protocols. E91 protocol [5], and BBM protocol [6] are based on entangled photons. GG02 protocol [7] and distributed-phase-reference (DPR) protocol [8] are continuous-variable protocols. Currently, long-distance QKD over 250 kilometers experiments have been reported [9] over fiber, and secure transmission of a quantum key has been performed over 144 km in free space [10]. Meanwhile, some QKD systems have already been commercialized [11].

Most of these QKD protocols rely on either polarization or phase of faint laser pulse as information carrier [12], the use of polarization encoding limits the degree of a photon to encode information. Unlike the limited degree of freedom on polarization or phase states, orbital angular momentum (OAM) states have attracted much

attention since there is an infinite OAM eigenstates in a single-photon [13–18]. In 2007, Molina-Terriza *et al.* have reviewed the use of OAM of photons and discussed its potential for realizing high-dimensional quantum spaces [14]. With the help of OAM entanglement, the group of Kwiat has beaten the channel capacity limit for linear photonic superdense coding [15]. In 2010, Leach *et al.* demonstrated the quantum correlations in optical angle-orbital angular momentum variables. Their experimental results of angular EPR correlations have established that angular position and angular momentum are suitable variables for applications in current quantum information processing. They also experimentally demonstrated the violation of a Bell inequality in two and eleventh dimensional OAM state-space [17, 18].

Apparently, the high capacity property of OAM states results in their applications in QKD protocol [19–21]. Recently, Gruneisen *et al.* proposed mutually unbiased bases (MUBs) with OAM for three dimensional quantum key distribution [20]. Malik *et al.* demonstrated an experimental implementation of a free-space 11-dimensional QKD system using OAM states [21]. In these protocols, OAM states are used to design the high-dimensional mutually unbiased bases. They are in principle the extension of BB84 protocol.

In this paper, we demonstrate a application for OAM entanglement in quantum key distribution. We experimentally realize a large-alphabet QKD protocol using OAM entanglement. This QKD protocol is quite different from the traditional one because the protocol is dependent on the OAM entanglement, and the security is ensured by the property of entangled photon pairs and the special information modulation. With the protocol, Alice and Bob can share keys without information rec-

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conciliation or privacy amplification. Meanwhile, there is no classical channel in the protocol.

This paper is organized as follows. In Sec. II, we detail the encoded states, and then present our QKD protocol. In Sec. III, we give the experimental results that certify our QKD protocol. In Sec. IV, we present the security analysis of the protocol. At last, in Sec. V, we discuss the results and draw our conclusions.

II. QUANTUM KEY DISTRIBUTION PROTOCOL USING OAM ENTANGLEMENT

Our proposed QKD protocol is dependent on the the encoded states. We will first introduce it in this section.

A. Encoded states

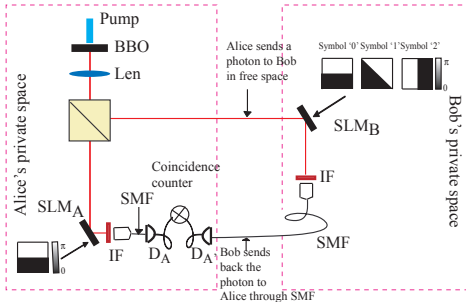


FIG. 1: (color online) Setup for the proposed QKD scheme.

The configuration considered for the protocol is shown in Fig. 1. The pump source is a Laguerre-Gaussian (LG) beam, which has zero orbital angular momentum. As OAM is conserved, the two-photon states generated from BBO crystal by SPDC process can be represented by [13, 16–18, 22]

$$|\Psi\rangle = \sum_{\ell=-\infty}^{\ell=\infty} |\phi\rangle_{\ell} = \sum_{\ell=-\infty}^{\ell=\infty} c_{\ell} |+\ell\rangle_A \otimes |-\ell\rangle_B, \quad (1)$$

where subscripts A and B denote signal (Alice's) and idler (Bob's) photons respectively, $|c_{\ell}|^2$ is the probability to generate an entangled photon pairs (one photon in signal arm with OAM $+\ell\hbar$ and the other photon in idler arm with OAM $-\ell\hbar$), $|\ell\rangle$ is the OAM eigenmode with mode number ℓ , and \hbar is the Plank constant divided by 2π . The OAM state of beam could then be changed by a phase filter, which is implemented by computer-controlled SLMs [23]. Here, the SLMs act as reconfigurable holograms. The modulated photons is collected via a single-mode fiber (SMF) which is fed to a single photon detector. As only the OAM eigenmodes $|\ell=0\rangle$ couples into the fiber (selected only for $|\ell=0\rangle$), a count in the detector indicates a detection of the state in which

the SLM was prepared for [18], where ℓ is the azimuthal index for OAM states of photons [19]. At last, the outputs from the detectors are fed to a coincidence counter. Experiments have justified that the generated two photons are in entanglement [13, 16–18, 22]. Using the modified Pointcaré sphere in an analogous fashion to polarization states, we use the sector state to encode symbol sequence in our QKD protocol.

A sector state is defined as an equally weighted superposition of $|\ell\rangle$ and $|\ell\rangle$ with an arbitrary relative phase, which is represented by a point along the equator [17]

$$|\theta_{\ell}\rangle = \frac{\sqrt{2}}{2}(e^{i\ell\theta} |+\ell\rangle + e^{-i\ell\theta} |-\ell\rangle), \quad (2)$$

where θ relates to the orientation of the sector state in the modified Pointcaré sphere. Actually, it is the angle between the sector state and the superposition state $\frac{\sqrt{2}}{2}(|+\ell\rangle + |-\ell\rangle)$ on the equator.

For an entangled photon pairs, the coincidence of one photon in sector state $|\theta_{A,\ell}\rangle$ and the other in state $|\theta_{B,\ell}\rangle$ is [17]

$$C(\theta_{A,\ell}, \theta_{B,\ell}) = |\langle \theta_{A,\ell} | \langle \theta_{B,\ell} | \Psi \rangle|^2 \propto \cos^2[\ell(\theta_A - \theta_B)]. \quad (3)$$

The high-visibility sinusoidal fringes of this joint probability could be used for the symbol retrieving. For example, if a $|\theta_{A,\ell}\rangle$ is fixed for one photon at Alice's side, and some discrete $|\theta_{B,\ell}\rangle$ with different angles are prepared for the other photon at Bob's side, the coincidence will be different for the different angles. At the same time, if the different angles here are the representation of different information at Bob's side, one could judge the different information from the different coincidence rates at Alice's side. We use these sector states to encode key sequences at Bob's side and recover the symbol information from the coincidence rate at Alice's side in our proposed QKD protocol.

B. Quantum key distribution protocol

As shown in the sketch of the setup in Fig. 1, the regions in the left box and the right box are Alice's and Bob's private places in our protocol, respectively. Based on the configuration and the sector states shown in Eq.(2), the proposed QKD protocol is designed as follows.

(1) With BBO crystal, Alice generates entangled photon pairs, named signal photons and idler photons. Alice keeps the signal photons for herself and sends the idler photons in the free-space channel to Bob.

(2) Alice selects a sector state $|\theta_{A,\ell}\rangle$ for the signal photons. Here, the sector state is implemented by a computer-controlled SLM_A with a special hologram in combination with SMF on the signal photons.

(3) At the same time, Bob will encode his symbol sequence with his sector states. He also selects the sector states using SLM_B with different phase holograms in combination with SMF on the idler photons. The corresponding sector states are $|\theta_{B,\ell}^0\rangle, |\theta_{B,\ell}^1\rangle, \dots, |\theta_{B,\ell}^{N-1}\rangle$, which are codes for key elements “0”, “1”, ..., “ $N-1$ ”, respectively. For a stream of key elements, Bob successively chooses the corresponding phase hologram and modulate them in his SLM. For each key element, the corresponding modulation continues for a regular time interval τ for enough coincidence counting. Of course, if the detectors have high enough detection efficiency, the regular time interval is not needed.

(4) Alice and Bob transmit the modulated photons to the detectors D_A and D'_A at Alice's private place through a single mode fiber, respectively.

(5) Alice performs a coincidence measurement at her site. According to the different coincidence rates, Alice can retrieve the key sequences prepared by Bob, so that they could share the same keys. Note that the suitable modulations for Bob in the 3rd step, mean that in the 5th step, the corresponding coincidences expressed in Eq.(3) are in distinct value regions.

On the other hand, in the above 1—5 steps, Alice and Bob replace each other, then Bob can recover keys sent by Alice. In other words, if there are two such setups, Alice and Bob can send keys to each other.

III. EXPERIMENTAL RESULTS

In order to testify this protocol by experiment, we setup an experimental system as Fig. 2, where a quasi continuous-wave, mode-locked (100MHz) 355nm laser is selected as the pump source. It is focused into a nonlinear crystal [β -barium borate (BBO)], which can generate OAM entangled photons through a frequency-degenerate type-I spontaneous parametric down-conversion (SPDC) process. The spatial light modulator are the product from Hamamatsu Photonics. The modulated photons is collected via a single-mode fiber (SMF) with 5 μ m. The single photon detectors are the detection modules from Perkin Elmer. The interference filters selected are at 710nm with 10nm bandwidth (Thorlabs product). In addition, some lens are used to illustrate the beam path is long enough in free space. Finally, The outputs from the detector modules are fed to a self-made coincidence counter. In order to implement the experiment, we let the two side (Alice and Bob) be symmetric. The detail of the experimental setup is shown as Fig. 2.

To verify the above protocol, we give experimental results at $N = 3$ and the sector states in Eq.(2) with $\ell = 1$. In the 3rd step of the protocol, we set the regular time interval $\tau = 1000ms$, which guarantees to produce no less than 500 entangled photon pairs in the time interval. Henceforth, we omit ℓ for simplic-

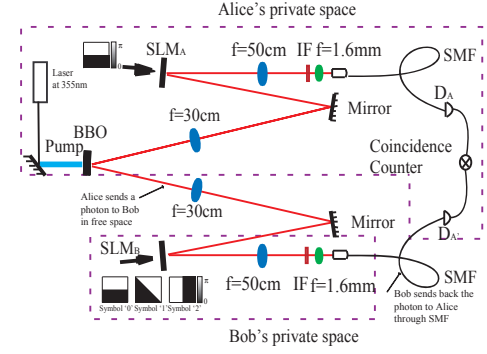


FIG. 2: (color online) Setup for the proposed QKD scheme. BBO:BaB₂O₄ nonlinear crystals; SLM_A :spatial light modulator for Signal photons; SLM_B :spatial light modulator for idler photons; SMF:single mode fiber; D_A :detector for signal photons; $D_{A'}$:detector for idler photons. In our protocol, the upper box and the lower box are Alice's and Bob's private places, respectively.

ity. We choose $|\theta_A = \frac{\pi}{2}\rangle, |\theta_B^0 = 0\rangle, |\theta_B^1 = \frac{\pi}{4}\rangle, |\theta_B^2 = \frac{\pi}{2}\rangle$. From Eq.(3), $C(\theta_A = \frac{\pi}{2}, \theta_B^0 = 0)$ is relatively small, $C(\theta_A = \frac{\pi}{2}, \theta_B^1 = \frac{\pi}{4})$ is middle, and $C(\theta_A = \frac{\pi}{2}, \theta_B^2 = \frac{\pi}{2})$ is relatively large.

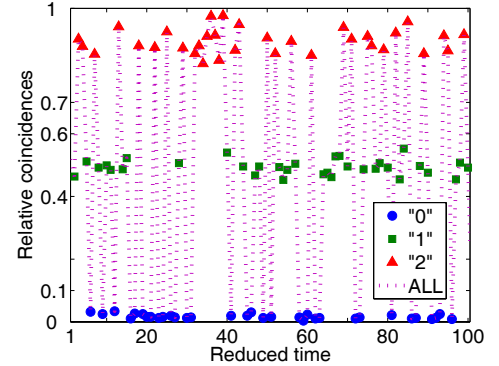


FIG. 3: (color online) The relative coincidences vary with the reduced time for key elements “0”, “1” and “2”, respectively.

In Fig.3, we show the relative coincidences versus the reduced time, which are for 100 successive keys from a key stream with length 10000. Here the relative coincidence is the ratio of photon coincidence counting during τ to the maximal counting 561 in our experiment, and the reduced time is the real time divided by τ . We find that the relative coincidences are near zero for the key element “0”, near one for the key element “2”, and around one-half for the key element “1”, which agrees with the calculated results from Eq.(3).

In Fig.4, we give the probability of relative coincidences for key elements “0”, “1” and “2”, as a statistic result from an experiment containing 10000 keys. It shows that they all obey Gaussian distribution due to the Gaussian noise of light sources. For key elements

TABLE I: the partial experiment results and corresponding keys at $\ell = 1$

Bob's key	0	1	1	2	2	1	0	2	0	1	0	2	1
θ_B	0	$\frac{\pi}{4}$	$\frac{\pi}{4}$	$\frac{\pi}{2}$	$\frac{\pi}{2}$	$\frac{\pi}{4}$	0	$\frac{\pi}{2}$	0	$\frac{\pi}{4}$	0	$\frac{\pi}{2}$	$\frac{\pi}{4}$
θ_A	$\frac{\pi}{2}$	$\frac{\pi}{2}$	$\frac{\pi}{2}$	$\frac{\pi}{2}$	$\frac{\pi}{2}$	$\frac{\pi}{2}$	$\frac{\pi}{2}$	$\frac{\pi}{2}$	$\frac{\pi}{2}$	$\frac{\pi}{2}$	$\frac{\pi}{2}$	$\frac{\pi}{2}$	$\frac{\pi}{2}$
coincidence	4	291	260	506	493	287	18	479	14	280	19	528	293
Relative coincidence	0.007	0.519	0.464	0.902	0.879	0.512	0.032	0.854	0.025	0.499	0.034	0.941	0.522
key recovered by Alice	0	1	1	2	2	1	0	2	0	1	0	2	1

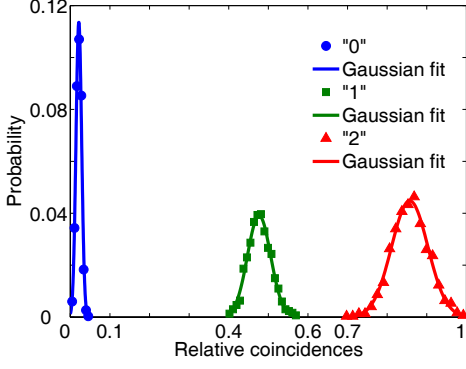


FIG. 4: (color online) The probability of relative coincidences for key elements “0”, “1” and “2”, respectively. The curves are corresponding Gaussian fits.

“0”, “1” and “2”, the values of relative coincidences are in the ranges $[0, 0.05]$, $[0.40, 0.57]$ and $[0.70, 1.0]$, respectively. There are large enough gaps between arbitrary two nearest ranges. In other words, the coincidence rates are in distinct value regions for different key elements. Therefore, Alice can judge the key element sent by Bob according to which region the value of the coincidence rate belongs to, i.e., Alice can recover Bob's keys. To test this, we let Bob send another 10000 keys in experiments. We find that Alice can fully recover Bob's keys with the decision criteria. The corresponding partial experimental results are illustrated in Table I.

IV. SECURITY ANALYSIS

Next, we will present our argument about the security of our QKD protocol from two aspects. One aspect is the security at the light way, and the other is the security against typical attacks.

A. Security at the light way

In the protocol, Alice generates the signal and idler photons from BBO crystal by SPDC. Then, Alice modulates a fixed phase on the photons in order to select special OAM states from the superposition of all OAM states from $\ell = -\infty$ to $\ell = \infty$. The modulated photons travel in SMF. Last, Alice take coincident measurement

and extract the key from the measurements. As shown in the left box in Fig.1, all these happen in Alice's site. During all the procedures, Eve can not access the signal photons. Therefore, the signal photons are safe.

As shown in the right box in Fig.1, Bob modulate the idler photons in his site. Eve can not access the idler photons during Bob's modulation. They are safe at the above procedure.

There are two chances for Eve to access the idler photons when idler photons travel in public quantum channels. As displayed in Fig.1, one chance is when the idler photons are transmitted from Alice to Bob in free spaces after Alice generates the OAM entangled photons. The other is when the idler photons are transmitted from Bob's private place to Alice's site in SMF after Bob modulates his information. For simplicity, we call the two chances the ATB chance and the BTA change, respectively. For the ATB chance, at that time, the state carried by idler photons is a superposition of all OAM states and does not have Bob's information. Furthermore, the idler photons are entangled with the signal photons. Hence, even Eve accesses these photons, she can not steal any Bob's information from the idler photon. Actually, Alice could detect this action since she keep the other entangled photon. For the BTA chance, there is only $|\ell = 0\rangle$ mode in the idler photons when they travel in SMF, and $|\ell = 0\rangle$ mode has no key information in Bob's encoding scheme. As entangled photon pairs are used in our protocol, Bob's information can be recovered only using coincidence measurement between idler and signal photons. However, in our protocol, Eve has no change to access signal photons, therefore, she also can not get any Bob's key information at the procedure.

From all the above, we find that Eve can not get Bob's key information for all the light way. Furthermore, the photon losses are unavoidable when photons travel in light ways nearly for all systems. Here Alice (Bob) recovers a key sent by Bob (Alice) using coincidence measurements. The corresponding coincidence counting rate is a statistical result, therefore, the value of key can also be recovered even at the condition that small fraction of photons loss.

B. Security against typical attacks

During QKD, there are many eavesdropping strategies for Eve to get key information. The typical attacks are the intercept-resend (IR) attack, the man-in-the-middle

(MIRM) attack, and the photon-number-splitting (PNS) attack, *et. al.* Eve can perform these attacks in the ATB chance or the BTA chance that mentioned above. In the following, we analysis them respectively.

(i)The IR attack: Eve measures out every signal emitted by Alice and prepares a new one, depending on the result obtained, that is given to Bob. As described above, in the ATB and the BTA chances, there is no difference between these idler photons. Eve can intercept and measure them. However, there is no meaning for these measurement results. Therefore, Eve can not get any key information. As entangled photon pairs are used, the photon resent by Eve will not satisfied with Eq.(3), so Alice can detect the eavesdropper.

(ii)The MIRM attack: Eve pretends to be Bob to Alice and simultaneously pretends to be Alice to Bob. QKD is vulnerable to this attack when used without authentication. In our protocol, Alice (Bob) can fully recover Bob's (Alice's) keys. They can also send deterministic keys to each other. If Alice and Bob have an initial shared secret, they can use these deterministic keys to authenticate each other.

(iii)The PNS attack: Weak pulses may contain more than one photon and Eve can simply keep some of the photons while letting the others go to Bob. In our protocol, many photons in a regular time interval τ generate a qudit, which is equivalent to the many-photon case. Eve can keep some of the photons while let the others go to Bob during one τ . As entangled photon pairs and sector states are used, Eve can't get key information carried by photons for she has no chance to perform coincidence measurements.

V. DISCUSSIONS AND CONCLUSIONS

In the paper, we have experimentally demonstrated the proposed large-alphabet QKD protocol with the entangled-photon in Bob's side carrying trits of information. Theoretically, Bob uses OAM as information carrier, so that he can encode more than one bits on his key sequences every time. We have analyzed the security of the protocol both from the light way and the typical attacks. The results show that the security of the protocol is ensured by the property of the entangled photons and the special fashion of the information modulation. The experimental results also show that Alice could recover fully Bob's information, so that Alice and Bob can share keys without information reconciliation or privacy amplification.

In principle, our QKD protocol have some advantages over the traditional QKD protocols. First, we use OAM states as the information carrier, there is in principle

no limit to how many bits encoded in each entangled photon pairs, which results in a potentially very large-alphabet size. Second, we utilize the entangled photons and the special fashion of the information modulation in the protocol, and recover the key sequences by coincidence counting. Since one photon is always kept in Alice's private space, Eve has no way to eavesdrop the key sequences during the protocol steps. All these assure the security of our proposed protocol. In addition, in the protocol, Alice and Bob do not need any classical communications for the key recovery, which makes the protocol efficient and simple.

In practice, the bits encoded in each entangled photon pairs is determined by the light source properties, noise intensity and the photon detection to distinguish the corresponding coincidences expressed in Eq.(3). Experimentally, we could recover four-based keys with the distinct coincidences if we set the regular time interval $\tau = 200ms$ so that more than 100 entangled photon pairs could be produced during the time interval. Hence, we got 5 four-based keys per second with 10 bits per second (bps) at this case. Currently, the coincidence rate is in the order 10^2 to 10^4 counts per second using different entangled photon sources, and the corresponding key generation rates are in the order 10 to 10^3 bps with our QKD. This is slower than QKD technologies based on weak coherent pulses. But, with the development of techniques about the photon detection and the generation of entangled photon pairs, the key generation rate will be improved greatly.

Generally, the practical implementing of QKD based on OAM states will confront two big problems, such as, decoherence by atmospheric turbulence and photon losses in quantum channel. Theoretically and experimentally, these two problems have been attracted a lot of attention [24, 25], and some solutions have been proposed to overcome these problems [26, 27].

Finally, as the keys can be recovered completely, the protocol can also be used to quantum authentication, quantum direct communication [28–30] and so on.

VI. ACKNOWLEDGMENT

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